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6. AUTHOR(S): R.L. AGGARWAL, J.J.ZAYHOWSKI, B.LAX

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Lincoln Laboratory, MIT
P.O. Box 73
Lexington, MA 02173-9108

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Calculated room-temperature threshold current densities for the visible II-VI ZnCdSe/ZnSe quantum-well diode lasers

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R. L. Aggarwal,[a] J. J. Zayhowski, and B. Lax
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts 02173-9108

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Room-temperature threshold current densities for the visible II-VI ZnCdSe/ZnSe semiconductor quantum-well diode lasers have been calculated using a simple model for the quantum-well gain and spontaneous radiative recombination rate. These results are compared with those for the infrared III-V GaAs/GaAlAs quantum-well lasers, calculated using the same model. By tailoring the epitaxial structure for optimum optical confinement, cw room-temperature operation of the ZnCdSe/ZnSe quantum-well lasers should be possible with threshold current densities as low as 400 A/cm^2 for a 1-mm cavity length and uncoated laser facets, assuming the problem of ohmic contacts to the epitaxial structure is resolved.

Blue-green lasing from the wide-band-gap II-VI ZnCdSe/ZnSe semiconductor quantum-well (QW) diode lasers was first reported in the pulsed mode at 77 K by Haase *et al.*[1] of 3M Co. in 1991. cw operation at 77 K has been reported by Jeon *et al.*,[2] Yu *et al.*,[3] and Sony Corp.[4] Jeon *et al.*[2] also obtained pulsed operation at temperatures between 77 K and room temperature. To date, the cw room-temperature operation has not been possible because of thermal problems resulting from large turn-on voltages and high threshold current densities ($\sim$1600 A/cm^2 in Ref. 2). Here we show that by tailoring the epitaxial structure for optimum optical confinement the calculated threshold current densities can be reduced to acceptable levels ($\sim$400 A/cm^2) for cw operation; we do not consider the problem of large turn-on voltages.

The room-temperature threshold current density J_{th} of $Zn_{0.83}Cd_{0.17}Se/ZnSe$ (henceforth ZnCdSe/ZnSe) QW lasers is calculated using the simple model of Dutta[5] for the QW gain and spontaneous radiative recombination rate. This model neglects the effects of strain, band nonparabolicity, intraband scattering, and excitonic[6] and nonradiative recombination. The optical confinement factor Γ is calculated for each of the following structures: (a) a single quantum well (SQW), (b) a multiple quantum well (MQW), and (c) a SQW in a step-index separate carrier confinement heterostructure (STINSCH). The J_{th} is obtained for the above structures by setting the threshold gain coefficient g_{th} equal to the round-trip laser cavity loss coefficient α divided by the corresponding Γ. These results are in good agreement with the experimental results of Jeon *et al.*[2] for a MQW structure. The calculated results for the ZnCdSe/ZnSe QW lasers are compared with similar results for the infrared III-V $GaAs/Ga_{0.5}Al_{0.5}As$ (henceforth GaAs/GaAlAs) QW lasers.

The maximum gain coefficient g_{max} due to interband transitions between the lowest-energy electron and heavy-hole subbands in a SQW of width L_w is given by[5]

$$g_{max}=K(f_e+f_{hh}-1), \tag{1}$$

$$K=[(2\pi q^2 m_{r,hh}|M_b|^2)/(\epsilon_0 m_0^2 ch\mu_w E_{0,hh1} L_w)], \tag{2}$$

$$|M_b|^2=m_0^2E_g(E_g+\Delta)/\{6m_e[E_g+(2/3)\Delta]\}, \tag{3}$$

$$f_\beta(E_{\beta 1})=\{1+\exp[(E_{\beta 1}-E_{f\beta}/k_BT]\}^{-1}, \tag{4}$$

where $f_\beta(E_{\beta 1})$, β=e, lh, hh, is the Fermi occupation factor for the lowest-energy electron (E_{e1}), light-hole (E_{lh1}), and heavy-hole (E_{hh1}) QW level, q is the electronic charge, $m_{r,hh}=m_e m_{hh}/(m_e+m_{hh})$ is the electron-heavy-hole reduced mass, m_e and m_{hh} are the electron and heavy-hole masses, $|M_b|$ is the average value of the interband momentum matrix element for the Bloch states of the electron and hole bands, ϵ_0 is the electron permittivity of vacuum, m_0 is the free electron mass, c is the velocity of light in vacuum, h is the Planck's constant, μ_w is the refractive index of the QW material at the lasing wavelength, $E_{0,hh1}=E_g+E_{e1}+E_{hh1}$ is the energy separation between the lowest-energy electron and heavy-hole QW levels, E_g is the energy gap, Δ is the spin-orbit splitting energy of the valence band, E_{fe} and $E_{fh}=E_{flh}=E_{fhh}$ are the quasi-Fermi energies for the electrons and holes, k_B is the Boltzmann's constant, and T is the temperature. The above expression for $|M_b|^2$ is a factor of 2 larger than that of Agrawal and Dutta,[5] but is consistent with that of Chinn *et al.*,[7] Asada *et al.*,[8] and Yamada *et al.*[9]

Assuming that the injected electron and hole carrier densities n_i and p_i are orders of magnitude larger than their thermal equilibrium values,

$$n_i=(\rho_e k_BT)\sum_j \ln\{1+\exp[(E_{fe}-E_{ej})/k_BT]\}, \tag{5}$$

$$n_i=p_i=(\rho_{lh}k_BT)\sum_j \ln\{1+\exp[(E_{fh}-E_{lhj})/k_BT]\} + (\rho_{hh}k_BT)\sum_j \ln\{1+\exp[(E_{fh}-E_{hhj})/k_BT]\}, \tag{6}$$

$$\rho_\beta=(4\pi m_\beta)/(h^2L_w), \tag{7}$$

where ρ_β is the density of states of a QW level, and $E_{\beta j}$ is the energy of the jth QW level, and m_{lh} is the light-hole mass. Equations (5) and (6) show that E_{fe} and E_{fh} are functions of n_i. Consequently, f_e, f_{hh}, and hence g_{max} are functions of n_i.

[a]Also at Department of Physics, MIT.

TABLE I. Room-temperature values of the material and device parameters for the GaAs/GaAlAs and ZnCdSe/ZnSe quantum-well lasers.

Parameter	GaAs/GaAlAs	ZnCdSe/ZnSe
m_e/m_0	0.071	0.16
m_{lh}/m_0	0.081	0.57
m_{hh}/m_0	0.45	1.0
E_g (eV)	1.42	2.40
Δ (eV)	0.34	0.43
δV_c (eV)	0.42	0.18
δV_v (eV)	0.21	0.08
μ_w	3.59	2.8
μ_b	3.26	2.7
α_a (cm^{-1})	3.5	3.5
L (mm)	1.0	1.0

The room-temperature values of the material and device parameters used in the calculations for the GaAs/GaAlAs and ZnCdSe/ZnSe QW lasers are given in Table I. δV_c and δV_v are the conduction and valence band offsets of the QW material relative to the barrier material, μ_b is the refractive index of the barrier material at the lasing wavelength, α_a is the average absorption coefficient of the well and barrier layers, and L is the laser cavity length. The values of m_e, m_{lh}, and m_{hh} for ZnCdSe are more than a factor of 2 larger than those for GaAs.

The nominal current density J_n required to achieve a given n_i is given by[5]

$$J_n = qL_wR, \tag{8}$$

where R is the total spontaneous interband radiative recombination rate per unit volume as follows:

$$R = [(16\pi^2 q^2 \mu_w |M_b|^2 N_w)/m_0^2 \epsilon_0 h^4 c^3 L_w)] \times (m_{r,lh} I_{lh} + m_{r,hh} I_{hh}), \tag{9}$$

$$I_\beta = \sum_j \int_{E_{0,\beta j}}^{\infty} E f_e(E_{c,\beta} + E_{ej}) f_\beta(E_{v,\beta} + E_{\beta j}) dE, \tag{10}$$

$$E_{0,\beta j} = E_g + E_{ej} + E_{\beta j}, \tag{11}$$

$$E_{c,\beta} = (m_{r,\beta}/m_e)(E - E_{0,\beta j}), \tag{12}$$

$$E_{v,\beta} = (m_{r,\beta}/m_\beta)(E - E_{0,\beta j}). \tag{13}$$

Here N_w is the number of QWs, and $m_{r,lh}$ is the electron-light-hole reduced mass. Calculated values of g_{max} for 100-Å-thick GaAs/GaAlAs and ZnCdSe/ZnSe SQWs are plotted as a function of n_i and J_n in Figs. 1(a) and 1(b). Our results for g_{max} vs n_i are consistent with those calculated by Ahn *et al.*[10] using a multiband effective mass theory and the density matrix formalism with intraband scattering taken into account. The injected carrier densities (the nominal current densities) required to achieve the same gain are approximately a factor of 3 larger for the ZnCdSe QWs than for the GaAs QWs. This is due to larger values of m_e, m_{lh}, and m_{hh} for ZnCdSe.

The Γ for the fundamental transverse mode of a MQW is[5]

$$\Gamma = (2\pi^2/\lambda_0^2)(\mu_a^2 - \mu_b^2) N_w L_w (N_w L_w + N_b L_b), \tag{14}$$

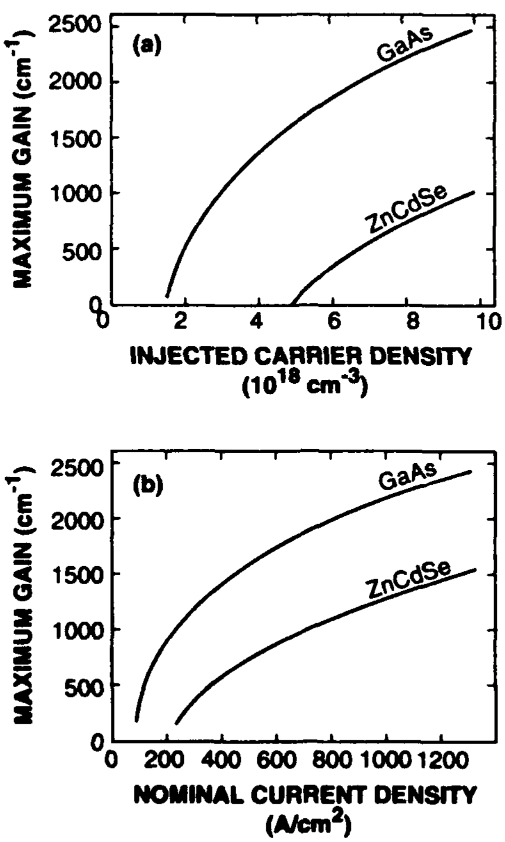

FIG. 1. Calculated room-temperature g_{max} vs (a) n_i and (b) J_n for 100-Å-thick GaAs/GaAlAs and ZnCdSe/ZnSe SQWs.

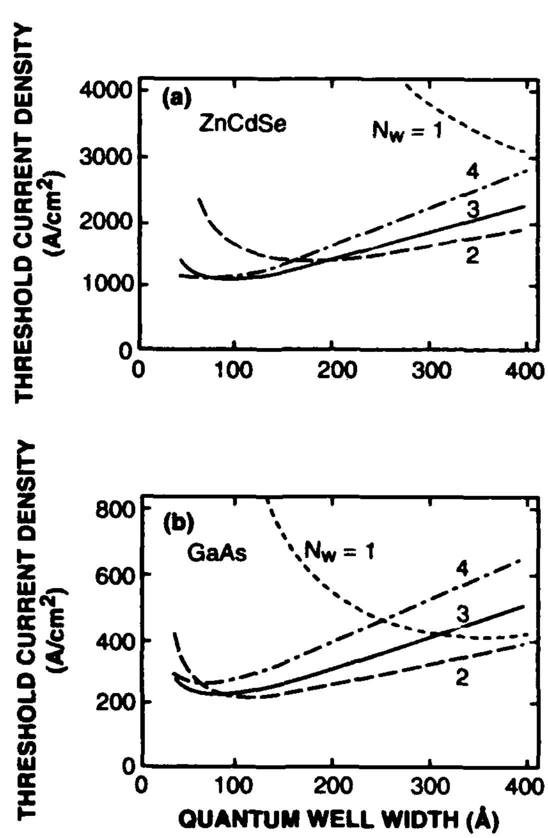

FIG. 2. Calculated room-temperature J_{th} vs L_g for (a) ZnCdSe/ZnSe and (b) GaAs/GaAlAs MQWs with L_b = 100 Å.

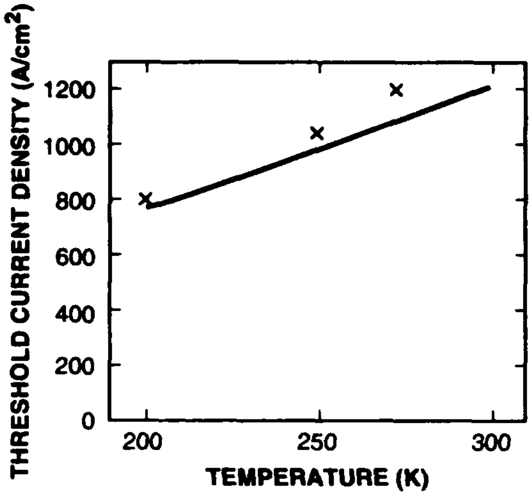

FIG. 3. Comparison of the calculated values for J_{th} for ZnCdSe/ZnSe MQWs ($N_w=6$, $L_w=60$ Å, and $L_b=100$ Å) with the experimental data of Jeon *et al.* (Ref. 2) for $T=200$, 250, and 273 K. The values of the band parameters were assumed to be temperature independent.

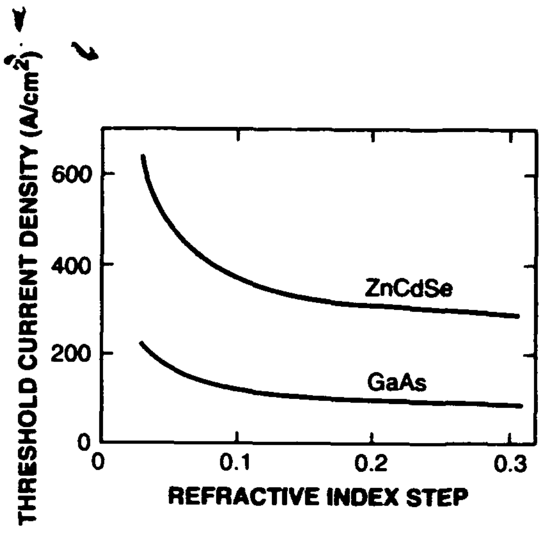

FIG. 4. Calculated room-temperature values of J_{th} vs $\Delta\mu=(\mu_c-\mu_b)$ for ZnCdSe and GaAs/GaAlAs quantum wells with an optimized STINSCH structure and $L_w=100$ Å.

$$\mu_a=(N_wL_w\mu_w+N_bL_b\mu_b)/(N_wL_w+N_bL_b), \tag{15}$$

where λ_0 is the wavelength of the laser radiation in vacuum, and N_b and L_b are the number and thickness of the barrier layers, respectively; for a SQW, $N_w=1$ and $N_b=0$. The α is given by

$$\alpha=\alpha_a-(1/L)\ln|r|^2, \tag{16}$$

where $|r|^2$ is the reflectance of the uncoated laser facets. The g_{th} is obtained by dividing α by Γ. Neglecting nonradiative recombination, J_{th} is obtained from J_n by setting g_{max} equal to g_{th}. The resulting J_{th} values are shown as a function of L_w in Figs. 2(a) and 2(b) for the ZnCdSe/ZnSe and GaAs/GaAlAs MQWs, using $L_b=100$ Å. The lowest values of j_{th} occur for $L_w\approx 100$ Å and $N_w=3$ or 4 in both systems. At this point, J_{th} is $\sim$1100 A/cm^2 for the ZnCdSe/ZnSe MQWs and $\sim$240 A/cm^2 for the GaAs/GaAlAs MQWs.

The calculated values of J_{th} for ZnCdSe/ZnSe MQWs with $N_w=6$, $L_w=60$ Å, and $L_b=100$ Å are compared with the pulsed data of Jeon *et al.*[2] for $T=200$, 250, and 273 K in Fig. 3. The relatively good agreement between the observed and calculated values of J_{th} provides some support for the theoretical model used here, even though exciton effects[6] have been neglected.

Further reduction in J_{th} can be achieved using a SQW in a STINSCH structure. As a result of the transparency condition, the threshold current is minimized by using only one QW in the STINSCH. For a SQW in an optimized STINSCH structure

$$\Gamma=(\pi L_w)/(4\sqrt{2}L_c), \tag{17}$$

where

$$L_c=\lambda_0/[\sqrt{2}\pi(\mu_c^2-\mu_b^2)^{1/2}] \tag{18}$$

is the optimized total thickness of the well and barrier layers and μ_c is the refractive index of the confinement layers. The calculated values of J_{th} for an optimized STINSCH structure are plotted in Fig. 4 against the refractive index step $\Delta\mu=(\mu_c-\mu_b)$ for the ZnCdSe/ZnSe and GaAs/GaAlAs QWs with $L_w=100$ Å. For $\Delta\mu=0.1$, J_{th} is reduced to less than 400 A/cm^2 for the ZnCdSe/ZnSe QWs and 125 A/cm^2 for the GaAs/GaAlAs QWs. ZnCdS, or some other II-VI ternary or quaternary material that can be lattice matched to the barrier layers and the substrate, may be a suitable candidate for the confining layers of the ZnCdSe/ZnSe STINSCH structure. The low value of J_{th} (400 A/cm^2) for ZnCdSe/ZnSe QW lasers with the STINSCH structure should make room-temperature cw operation possible, once the problem of ohmic contacts to the epitaxial structure is resolved.

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